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Radion effects on the production of an intermediate-mass scalar and Z at LEP II

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Abstract

We have studied the $e^+e^- \rightarrow Z\phi_i \rightarrow Zjj$ process, where ϕ_i is the Higgs and/or radion bosons. The implications of the radion effects on the preliminary ALEPH data are also discussed. The case of the lighter radion than Higgs boson is disfavored by the ALEPH analyses of the b tagged four-jet data, since the radion predominantly decays into two gluon jets due to the QCD trace anomaly. If the radion is highly degenerate in mass with the Higgs, the cross section can be increased more than at one sigma level, with natural scale of the vacuum expectation value of the radion.

I. INTRODUCTION

The standard model (SM) has been very successful in describing the known electroweak interactions of gauge bosons and fermions. Nevertheless one of the most crucial ingredients of the SM, the Higgs boson, has not been experimentally discovered yet [1]. The Higgs mechanism is responsible for the electroweak symmetry breaking in the SM, of which the effects should appear by the scale below $(8\pi\sqrt{2}/3G_F)^{1/2} \sim 1$ TeV for the preservation of unitarity in the $W_L W_L \rightarrow W_L W_L$ process [2]. Hence the primary efforts of the future collider experiments are to be directed toward the search for Higgs bosons.

The search techniques for Higgs bosons according to the Higgs mass range have been extensively studied in the literature [3]. Light Higgs bosons with mass below 107.7 GeV are excluded by LEP-II experiments at the 95% confidence level [4]. For *heavy* Higgs bosons ($m_h \gtrsim 2m_Z$), the experimental search is rather straightforward by observing the Higgs decay into a Z boson pair, or by studying WW scattering at e^+e^- or hadron colliders [5]. For the *intermediate*-mass ($m_Z < m_h \lesssim 2m_Z$), one of the best reactions for their detection is known to be $e^+e^- \rightarrow Z^* \rightarrow Zh$ (see the corresponding Feynman diagram in Fig. 1) [6]. The Higgs boson in this mass range decays mainly into $b\bar{b}$. The direct physics background from the continuum production of $e^+e^- \rightarrow Zb\bar{b}$ has been also discussed in the literature.

Theoretically, the Higgs boson holds a distinctive position in understanding the physics beyond the SM. The existence of the Higgs boson in the SM, as a fundamental scalar particle, causes the well-known gauge hierarchy problem: It is unnatural that the Higgs mass at the electroweak scale is protected from the presence of the enormous Planck scale. This gauge hierarchy problem is the main motivation for various models of new physics, such as supersymmetric models, technicolor models, and extra dimensional models. Among these, an extra-dimensional model recently proposed by Randall and Sundrum (RS) requires the existence of another scalar field, called the radion, of which the mass can be compatible with the Higgs mass [7].

In this report, we study the radion effects on the $e^+e^- \rightarrow Z\phi_i \rightarrow Zjj$ process, where the

ϕ_i is a Higgs boson and/or radion, and j denotes a hadronic jet. Recently, an exciting, even preliminary, news has come from the ALEPH group [8]. From the analyses of the 237 pb^{-1} of data collected at \sqrt{s} up to 209 GeV, the ALEPH has measured three standard deviation from the SM continuum background. This result is compatible with the SM Higgs of mass around 114 GeV. Another unusual result is that the cross section with the SM Higgs is still high; the standard deviation is between 1σ to 2.5σ [8]. If this result remains valid in the future, the radion, if degenerate in mass with the Higgs, can be one of the best candidates for the explanation of the excess. We caution the reader that due to the small number of events and the presence of background in the current ALEPH data, it is very impetuous to draw any physical conclusion at this moment.

In the RS model, the hierarchy problem is solved by a geometrical exponential factor, called a warp factor [7]. The spacetime has a single S^1/Z_2 orbifold extra dimension with the metric

$$ds^2 = e^{-2kr_c|\varphi|} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\varphi^2, \quad (1)$$

where the φ is confined to $0 \leq |\varphi| \leq \pi$. Two orbifold fixed points accommodate two three-branes, the hidden brane at $\varphi = 0$ and our visible brane at $|\varphi| = \pi$. The allocation of our brane at $|\varphi| = \pi$ renders a fundamental scale m_0 to appear as the four-dimensional physical mass $m = e^{-kr_c\pi} m_0$. The hierarchy problem can be answered if $kr_c \simeq 12$. In this model, very critical is the stabilization of the compactification radius r_c : Without a stabilized radius, we should impose a fine-tuning constraint between the matter densities on the two branes, which causes non-conventional cosmologies [9]. Several scenarios for the stabilization mechanism have been proposed, where the radion modulus ϕ can be significantly lighter than the geometrically suppressed Planck scale on the visible brane, $\Lambda \sim \mathcal{O}(\text{TeV})$ [10]. Various phenomenological aspects of the radion at colliders have been studied in the literature: The decay modes of the radion according to its mass range are different from those of the Higgs (e.g., its dominant decay mode with mass below $2m_Z$ is into two gluons) [11]; without a curvature-scalar Higgs mixing, the radion effects on the oblique parameters

of the electroweak precision observations are small [12]; the electroweak mixing angle can undergo a substantial correction if the mass and vacuum expectation value (VEV) of the radion are below TeV [13]; the radion effects on the phenomenology at low energy colliders [14] and at high energy colliders [15] have been also discussed (e.g., a lower bound of 35 GeV on the radion mass is obtained from the LEP-I bound on the 60 GeV Higgs mass).

The interactions of the radion ϕ with the SM particles show similar behaviors to those of the Higgs boson. The interaction Lagrangian is

$$\mathcal{L} = \frac{1}{\Lambda_\phi} \phi T_\mu^\mu, \quad (2)$$

where the T_μ^μ is the trace of the conserved and symmetrized energy-momentum tensor of the SM fields, and the Λ_ϕ is the VEV of the radion. The coupling of the radion with a fermion or gauge boson pair is the same as that of the Higgs, except for a factor of (v/Λ_ϕ) . The v is the VEV of the Higgs. The massless gluons and photons also contribute to the T_μ^μ , due to the trace anomaly. It is known that the trace anomaly appears since the scale invariance of massless fields is broken by the running of gauge couplings [16]. Thus the interaction Lagrangian between two gluons and the Higgs or the radion is

$$\mathcal{L}_{h(\phi)-g-g} = \left[\left(\frac{v}{\Lambda_\phi} \right) \{b_3 + I_{1/2}(z_t)\} \phi + I_{1/2}(z_t) h \right] \frac{\alpha_s}{8\pi v} \text{Tr}(G_{\mu\nu}^C G^{C\mu\nu}), \quad (3)$$

where $z_t = 4m_t^2/m_h^2$, and the QCD beta function coefficient is $b_3 = 11 - 2n_f/3$ with the number of dynamical quarks n_f . The loop function $I_{1/2}(z)$ is defined by

$$I_{1/2}(z) = z[1 + (1 - z)f(z)], \quad (4)$$

where the $f(z)$ is

$$f(z) = \begin{cases} \arcsin^2(1/\sqrt{z}), & z \geq 1, \\ -\frac{1}{4} \left[\ln \left(\frac{1+\sqrt{1-z}}{1-\sqrt{1-z}} \right) - i\pi \right]^2, & z \leq 1. \end{cases} \quad (5)$$

It is to be noted that the phenomenology of radions can be determined by two parameters, m_ϕ and Λ_ϕ . For the intermediate-mass radion, the dominant decay rate into gg is larger than that into $b\bar{b}$ by an order of magnitude.

Let us now review the ALEPH results [8]. By using both a neural-network-based stream (NN) and a cut-based stream, the ALEPH group analyzed the final states most from the process $e^+e^- \rightarrow HZ$: the four-jet final states ($Hq\bar{q}$), the missing energy final states ($H\nu\bar{\nu}$), the lepton pair final states (Hl^+l^- where l denotes an electron or muon), and the tau lepton final states ($H\tau^+\tau^-$ and $H \rightarrow \tau^+\tau^-$, $Z \rightarrow q\bar{q}$). Common discriminant for the event selection is the reconstructed Higgs boson mass. As a second discriminant, the neural network output is used for the four-jet NN analysis while the sum of the b tagging neural network output values is used for the missing energy NN and lepton pair selections.

We are interested in the radion effects on the circumstance where the lighter scalar is produced on-shell. If the radion is much heavier than the Higgs boson, the ordinary analyses with the SM Higgs remain intact. The opposite possibility of the presence of lighter radions is disfavored, since the ALEPH analysis of the b -tagged data is compatible with the SM Higgs boson hypothesis, while a radion with mass around 114 GeV predominantly decays into two gluons.

If the radion is almost degenerate in mass compared with the Higgs, the cross section for the process $e^+e^- \rightarrow Z\phi_i \rightarrow Zjj$ is to be modified. With the degenerate radion involved, two hadron jets can be either $b\bar{b}$ jets or gg jets, while the SM Higgs boson at 114 GeV mass predominantly decay into $b\bar{b}$ jets. The radion effect is casted into the ratio between the total cross sections with and without the radion involved:

$$\begin{aligned}
\frac{\sigma_{h+\phi}^{Zjj}}{\sigma_h^{Zjj}} &\simeq \frac{\sigma_{h+\phi}^{Zb\bar{b}} + \sigma_\phi^{Zgg}}{\sigma_h^{Zb\bar{b}}} \\
&= \frac{|M_{e^+e^- \rightarrow Zh} D_h M_{h \rightarrow b\bar{b}} + M_{e^+e^- \rightarrow Z\phi} D_\phi M_{\phi \rightarrow b\bar{b}}|^2}{|M_{e^+e^- \rightarrow Zh} D_h M_{h \rightarrow b\bar{b}}|^2} + \frac{\sigma(e^+e^- \rightarrow Z\phi) Br(\phi \rightarrow gg)}{\sigma(e^+e^- \rightarrow Zh) Br(h \rightarrow b\bar{b})} \\
&= 1 + 2 \left(\frac{v}{\Lambda_\phi} \right)^2 \Re \left(\frac{D_\phi}{D_h} \right) + \left(\frac{v}{\Lambda_\phi} \right)^4 \left| \frac{D_\phi}{D_h} \right|^2 + \left(\frac{v}{\Lambda_\phi} \right)^2 \frac{\Gamma_h \Gamma_{\phi \rightarrow gg}}{\Gamma_\phi \Gamma_{h \rightarrow b\bar{b}}},
\end{aligned} \tag{6}$$

where M is the scattering amplitude, and $D_i(q^2)$ is the propagation factor for the i -th scalar particle. Since the narrow width approximation, $|D_i|^2 \simeq (\pi/\Gamma_i m_i) \delta(s - m_i^2)$, with the degenerate assumption ($m_h \approx m_\phi$) implies

$$\Re\left(\frac{D_\phi}{D_h}\right) = \frac{(s - m_h^2)(s - m_\phi^2) + \Gamma_h \Gamma_\phi m_h m_\phi}{(s - m_\phi^2)^2 + \Gamma_\phi^2 m_\phi^2} \Big|_{(\sqrt{s} \approx m_h \approx m_\phi)} \approx \sqrt{\frac{\Gamma_h}{\Gamma_\phi}}, \quad (7)$$

the ratio become

$$\frac{\sigma_{h+\phi}^{Zjj}}{\sigma_h^{Zjj}} = 1 + 2 \left(\frac{v}{\Lambda_\phi}\right) \sqrt{\mathcal{R}} + \left(\frac{v}{\Lambda_\phi}\right)^2 \mathcal{R} \left[1 + \frac{\alpha_s}{12\pi^2} \frac{m_h^2}{m_b^2} \frac{|b_3 + I_{1/2}(z_t)|^2}{(1 - z_b)^{3/2}} \right]. \quad (8)$$

From the fact that the decay-rate ratio Γ_h/Γ_ϕ is inversely proportional to $(v/\Lambda_\phi)^2$, we have defined \mathcal{R} in Eq. (8) by

$$\mathcal{R} \equiv \left(\frac{v}{\Lambda_\phi}\right)^2 \frac{\Gamma_h}{\Gamma_\phi} \simeq \frac{1 + C_{\tau b} + C_{\text{QCD}}(M_{jj}) |I_{1/2}(z_t)|^2}{1 + C_{\tau b} + C_{\text{QCD}}(M_{jj}) |b_3 + I_{1/2}(z_t)|^2}, \quad (9)$$

where M_{jj} is the reconstructed scalar mass, $z_x = 4m_x^2/M_{jj}^2$, and the $C_{\tau b}(M_{jj})$ and $C_{\text{QCD}}(M_{jj})$ are,

$$C_{\tau b} = \frac{1}{3} \left(\frac{m_\tau}{m_b}\right)^2 \left(\frac{1 - z_\tau}{1 - z_b}\right)^{3/2}, \quad (10)$$

$$C_{\text{QCD}}(M_{jj}) = \frac{\alpha_s^2}{12\pi^2} \left(\frac{M_{jj}}{m_b}\right)^2.$$

Here we have taken into account of $b\bar{b}$, $\tau^+\tau^-$, and gg as the decay modes of an intermediate-mass scalar particle. The difference between the Higgs and radion masses is assumed to be below the mass resolution at e^+e^- colliders. Since the QCD beta function coefficient b_3 is 7 for $n_f = 6$, the \mathcal{R} is less than one. Thus the ratio $\sigma_{h+\phi}^{Zjj}/\sigma_h^{Zjj}$ is larger than one, implying that the presence of degenerate radions increases the cross section. And the enhancement can be substantial since $\mathcal{R}(m_h = 114 \text{ GeV}) = 0.08$.

Now we discuss the implications of the radion effects for the ALEPH results. In this degenerate case, it is possible to explain one of the preliminary ALEPH results; the cross section is measured still higher than the SM Higgs prediction. The 1σ and 2σ excesses in the cross section at $\sqrt{s} = 207 \text{ GeV}$ and $\int \mathcal{L} dt = 216.1 \text{ pb}^{-1}$ can be explained by Higgs-radion degeneracy with $\Lambda_\phi = 2.2 \text{ TeV}$ and $\Lambda_\phi = 1.4 \text{ TeV}$, respectively. The Higgs mass m_h is set to be 114 GeV, used as the QCD scale in α_s . When the b tagging of the jets from the Higgs decay is highly performed as in the high purity data selection of the ALEPH [8], the relevant quantity to signal the radion effects is

$$\frac{\sigma_{h+\phi}^{Zb\bar{b}}}{\sigma_h^{Zb\bar{b}}} = 1 + 2 \left(\frac{v}{\Lambda_\phi} \right) \sqrt{\mathcal{R}} + \left(\frac{v}{\Lambda_\phi} \right)^2 \mathcal{R}. \quad (11)$$

For $\Lambda_\phi = 2.2$ TeV which would yield 1σ excess in the 216.1 pb^{-1} data, the radion effects would lead to 0.34σ excess in the cross section compared to that without the radion effects. When the luminosity increases into 700 pb^{-1} , the 1σ and 2σ excesses in the cross section correspond to $\Lambda_\phi = 3.1$ TeV and $\Lambda_\phi = 2.0$ TeV, respectively. It is concluded that highly degenerate radions with the SM Higgs can be a good explanation for the excess of the scalar production accompanying Z at e^+e^- colliders.

In summary, we studied the $e^+e^- \rightarrow Z\phi_i \rightarrow Zjj$ process, where ϕ_i is the Higgs and/or radion particles. In the case of the lighter radion than the Higgs, the QCD trace anomaly renders the radion to decay dominantly into gg , which is not compatible with the ALEPH b -tagged results. If the radion is highly degenerate in mass with the Higgs, the cross section can be increased more than at one sigma level. This can be one of the most natural explanations for the preliminary ALEPH results of the excess in the cross section with the SM Higgs.

ACKNOWLEDGMENTS

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FIGURES

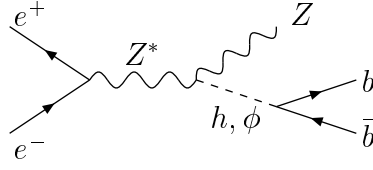


FIG. 1. The Feynman diagram of the $e^+e^- \rightarrow Z\phi_i \rightarrow Zb\bar{b}$ process with the Higgs and radion.